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Measurement of Finger Pad Forces and Friction using Finger Nail Mounted Strain Gauges

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ABSTRACT

There are currently few techniques for measuring *in-vivo* the forces exerted by the finger pads when handling objects and friction levels in the interface. Those that exist are intrusive and affect the manner in which an object is gripped or the interface between finger and object. A non-intrusive method would enable data to be gathered on object grip and manipulation that could improve designs to aid usability and inclusivity.

The aim of this work was to assess the feasibility of determining finger pad forces and friction between a finger pad and a surface using strain gauges mounted to finger nails. The index finger and thumb were assessed as these have been shown to be used most for gripping in everyday tasks. Initially Digital Image Correlation was used to study strain across whole finger nails during a loading event to establish where it would be best to mount the strain gauges. After attachment of the strain gauges, tests were carried out normally loading finger pads against a force plate to determine strain/force relationships and the effects of slight finger side roll. Sliding tests were then also carried out in dry and lubricated conditions to see how strain varied when normal force was kept constant.

Clear relationships have been established between strain and force that could be used to calibrate from measurements taken during actual object manipulation. Changing friction has also been shown to affect strain.

1 INTRODUCTION

Measurement of how hard we grip objects while using them is essential information for improving inclusive design and enhancing design for function, leading to products more appropriate for their intended use. Friction force also plays an important role as it has a significant effect on the way humans perceive and handle objects, it is an essential part of the feedback/forward grip control system [1]. For example, we will over-grip if an object feels as if it may slip while we are using it. This will then impede manipulation of the object and may decrease its functionality.

There has been a constant evolution to the way in which grip is classified. It was concluded by Napier [2] that the various forms of hand grip could be summarised as one of two main types: the power grip, when an object is clamped between flexed fingers and the palm, with counter pressure provided by the thumb; and the precision grip, when an object is pinched between the flexor aspects of the finger and the opposing thumb. The motivation for this simplified classification was to allow a universal description of grips, obtained from a functional and anatomical perspective, that could aid clinicians in evaluating patient function. Cutkosky et al. [3] presented a more in-depth taxonomy of grip, splitting power grip into nine types and precision grip into seven as shown by Figure 1. This taxonomy is not comprehensive, as it omits a number of common grasp types, for example gripping a pen or pencil, however this is still the most extensive and widely used taxonomy. It was initially informed by observation of activities of daily living, and then used to classify grip types in further studies such as those carried out by Lee et al. [4] and Zheng et al. [5]. Examination of the different grip studies showed that the most common grip types were the “Medium Wrap” and “Thumb-Index Finger” (see Figure 1 for detail of these) and the digits most often implemented in studies were the index finger and thumb. These were therefore chosen as the focus of investigation in this work.

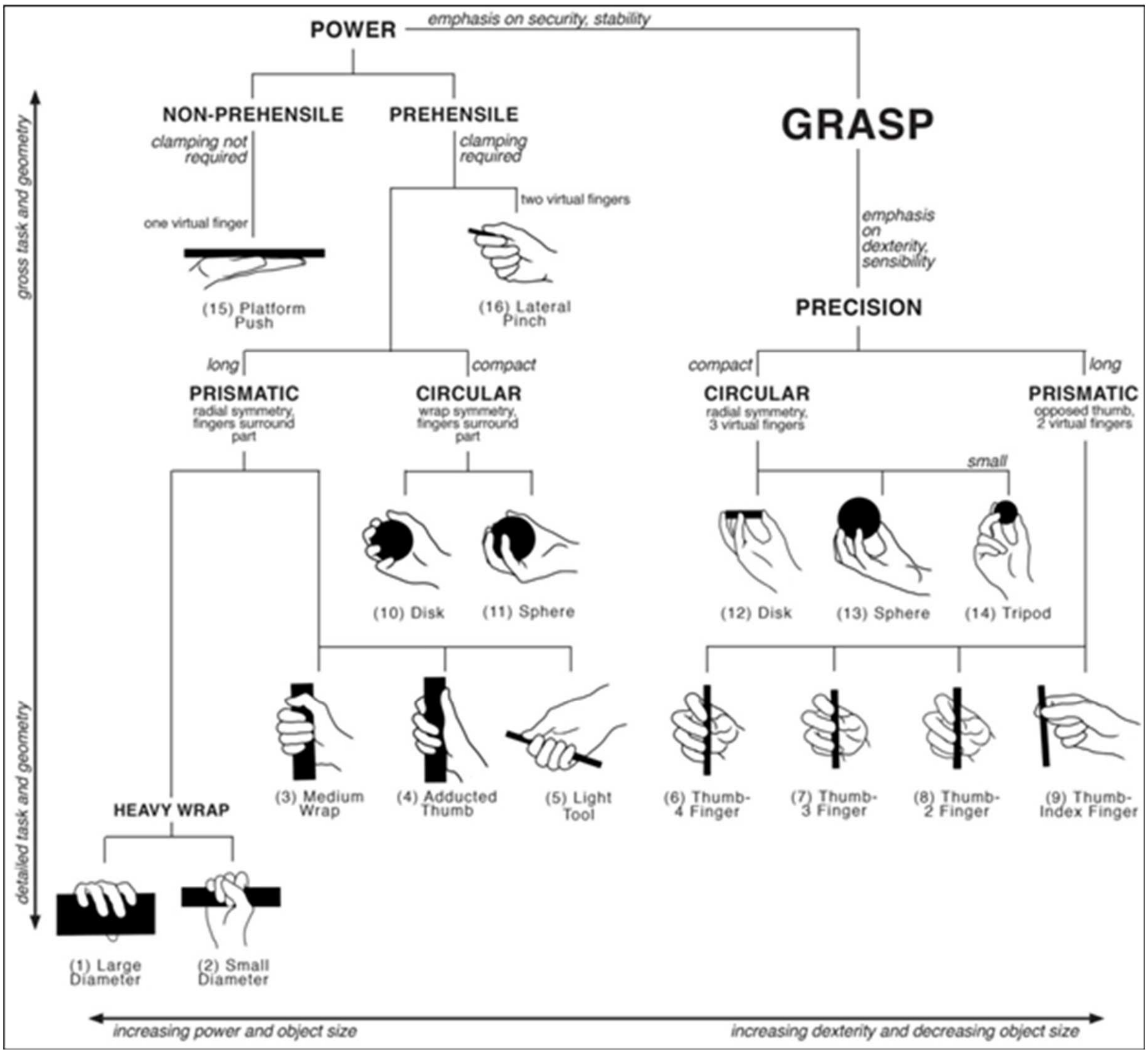


Figure 1. The Cutkosky Grip Taxonomy [3]

The most commonly used method for grip measurements has been the application of a force sensitive film between the finger and object. For example, Nicholas et al. utilised a Tekscan© pressure sensor to measure the force distribution and contact area of the hand when gripping, pushing and pulling a cylinder [6]. While using the Tekscan system gave a detailed force distribution map providing an indication of individual finger forces, the sensor is intrusive and is therefore affecting the values recorded.

An alternative method for measuring *in-vivo* finger pad forces was proposed by Sun et al. [7], and employed imaging apparatus to measure the colouration of the finger nail with increasing load. The change in colouration was caused by increased pressure beneath the nail upon loading, limiting blood flow. It was found that there was a linear correlation between the normal force applied by the finger pad and the colouration up to a level of 1N at which point the relationship began to level off. While this method is non-intrusive, it does not allow measurements to be taken while the finger is being moved, which limits its application.

Strain gauges attached to the finger nail have been used to provide a non-intrusive measure of applied forces. Saitou et al. [8] investigated the release between the ball and finger pads during baseball pitching by attaching strain gauges to the surface of finger nails (actual forces were not determined). The subjects then pitched towards a net and the strain in the nails was recorded. The results showed mostly compressive strains on the finger nails particularly on the front edge.

A limited study conducted by Sakai et al. [9] investigated the relationship between normal force (measured using a force plate) and finger nail strain in the longitudinal and lateral orientations at three positions on the finger nail. The study used the index finger on the right hand of ten subjects. There were considerable differences in measurements depending on where the gauges were located on the nail and it was also reported that there were large discrepancies in lateral strains between subjects; however, the values of strain recorded in the longitudinal direction were relatively consistent. Figure 2 shows that the strains recorded in the finger nail, as the finger was compressed, increased in the positive direction with force. This indicates that the finger nail lengthened as the finger was compressed onto the surface.

Research conducted by Teo [10] showed that strain gauges bonded at the distal central position of the finger nail were effective at determining the forces experienced in the finger pads, particularly in the longitudinal orientation. It was observed by Teo [10] that as the load applied to the index finger was increased, longitudinal strain in the finger nail decreased linearly, indicating that the finger nail was in compression. Teo's results [10] differ to those found by Sakai et al. [9] as the direction of strain is reversed. This method was validated using a pinch grip test and was found to be successful for the middle and index fingers in the longitudinal direction, but less reliable in the lateral direction. There were also large discrepancies present with data collected for the thumb in both orientations. The unreliability of lateral strain results in both studies was attributed to the 'rolling' of the finger during measurements. It was also suggested by Sakai et al. [9] that this effect may have been due to the asymmetry of the finger about its longitudinal axis.

Measurement of friction forces in a sliding finger pad interface is usually limited to measurements taken while moving a finger over a force plate (see [1] for examples). This restricts the applications that can be investigated and rules out measurements while actual tasks are being carried out. A new approach is needed to facilitate measurements while a finger is moving on an actual object.

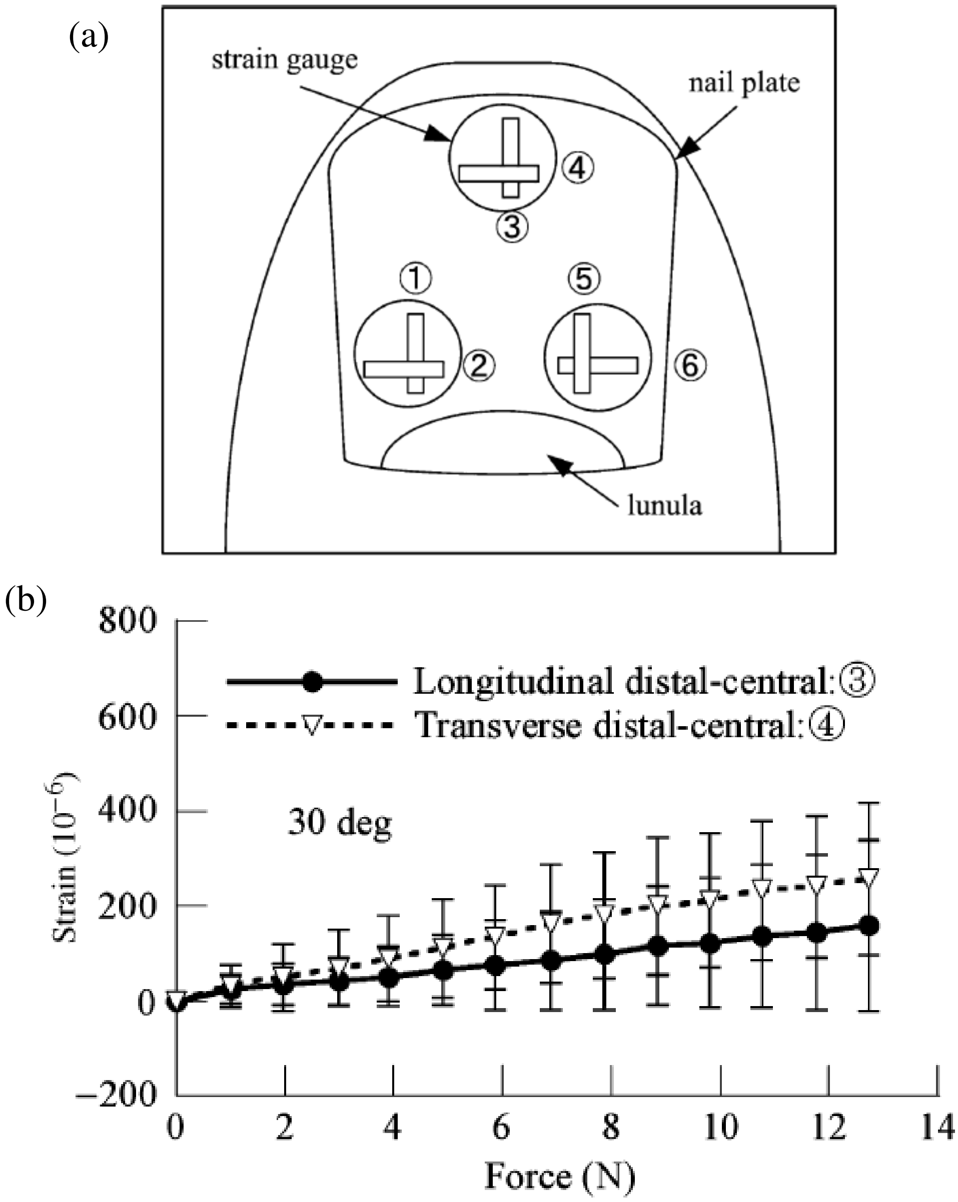


Figure 2. Finger nail Strain Measurements for Normal Loading at a Finger Angle of 30° (a) Position of Strain Gauges; (b) Longitudinal and Transverse (Lateral) Distal-Central Strain Values [9]

In carrying out measurements involving the finger pad skin, the underlying (subcutaneous) tissue and a finger nail, the properties and behaviour of each have to be considered to enable the optimal approach to be used in taking the measurements and in interpreting the results. This has not been done in previous research of this nature. The finger pad skin is made up of two layers; the dermis and the epidermis. The epidermis is the outermost layer of skin and can be further deconstructed into its constituent layers with the stratum corneum being the outermost. The dermis is made up of collagen and elastin fibres, which are responsible for the elastic properties of skin. Collagen fibres make up around 70% of the dermis and are responsible for strength, tension and elasticity [11].

The finger nail is connected to the skin of the finger pad by a layer of subcutaneous tissue, bone and the nail bed [12] (see Figure 3). The subcutaneous tissue is also known as “pulp” and is primarily made up of fat cells. The underside of the nail is in direct contact with the finger pad pulp. The skin and the pulp will be directly involved in the transmission of forces from the finger pad/object interface to the finger nail so how this occurs will depend on their properties and behaviour under load. The properties of the nail are also important in dictating how the strain manifests itself.

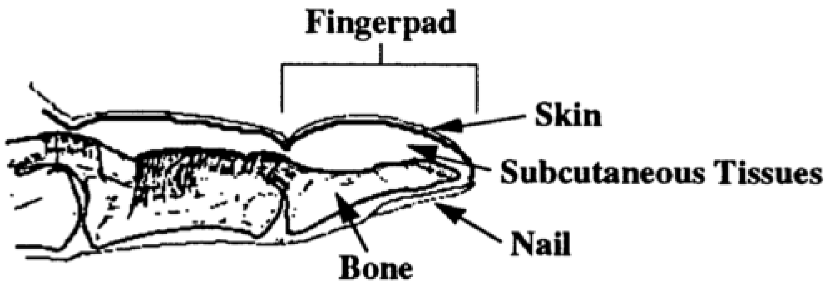


Figure 3. Cross-Sectional View of a Finger [12].

Figure 4 shows how the orientations and locations of the finger nail were defined for this work. As noted in previous work, the strain behaviour of the finger nail varies considerably depending on the position of measurement [11]. This can be attributed to the geometry of the nail itself, for example the finger nail is at its thickest at its distal edge [13]. This has the effect of increasing resistance to deformation at this position. Farren et al. [14] also found that the finger nail is almost twice as tough in the longitudinal orientation when compared to the transverse. This accounts for the considerable discrepancy in data collected by both Sakai et al. [9] and Teo [10] when investigating lateral strain in finger nails during the application of normal force. This emphasises the importance of maintaining a high level of consistency when positioning strain gauges on the finger nail during experiments.

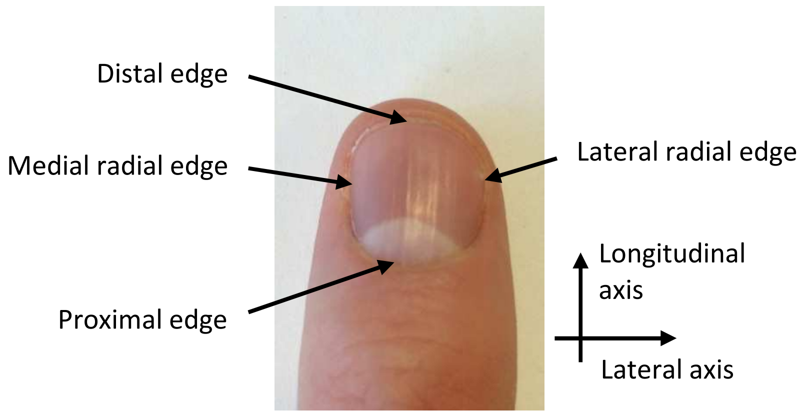


Figure 4. Index Finger Nail and Definitions

Previous work has shown the validity in the method of using strain gauges to measure normal force, and that the finger nails tend to behave linearly with normal force. There were, however, a number of factors that needed to be further understood concerning the relationship between normal force and finger nail strain, such as the effects of normal force on lateral strain and the effects of finger roll. There is little work concerning the measurement of frictional force using methods that could be employed while tasks are being carried out, but the use of strain gauges seems a viable approach.

The aim of this project was therefore to determine an experimental procedure to accurately measure grip force using strain gauges mounted on finger nails, building on the pilot studies carried out previously [8, 9, 10] and to then extend the work to carry out finger pad sliding friction force measurements. This would be an effective way of measuring the *in-vivo* forces experienced by the finger pads when carrying out everyday tasks without altering the finger pad-object interface.

Knowledge of forces applied by a person using a product or interacting with a surface could help improve designs to increase usability. This is particularly important at the moment as there is an ageing population for whom inclusive design is critical. Many tasks of daily living could be made easier such as opening food packaging or preparing meals. This would ensure that people with strength/dexterity impairments can still prepare food and maintain their independence.

2 EXPERIMENTAL DETAILS

2.1 Strain Gauge Selection and Application

In order to select the best location to mount the strain gauges on the finger nails a full strain map of the finger nails was required. This was achieved using Digital image Correlation (DIC). DIC is a technique that uses a Charged Coupled Device CCD camera to record a series of images of a component's surface, tracking unique subsets of a surface pattern between images. This allows displacement of any point on the surface, and subsequently Lagrangian strain to be determined. This form of strain measurement compares the deformation at any given moment to the reference image, which is of the specimen prior to load application. 3D DIC uses two cameras in a stereovision arrangement, tracking both in and out of plane displacement. In order to track these points it is necessary to apply a speckle pattern to the surface of the component (see Figure 5a for patterns applied to finger nails). This pattern must be random, high contrast, sharp grey scale and have a scale relevant to the displacement being measured. In order to achieve the highest possible resolution, one element of the pattern should occupy a single pixel of a recorded image. For this project the software used was VIC–3D™ v7 from Correlated Solutions. Using this technique allowed full field strain measurement as opposed to single point measurement when using strain gauges.

During these measurements an index finger and a thumb were pushed against a force plate at an angle of 30° and a force of 10N while the DIC images were taken.

It can be seen from Figure 5b that there was low compressive (negative) strain in the longitudinal direction in bulk of the index finger nail before the initiation of sliding. There was a region of raised compressive strain towards the distal edge of the nail, and positive strain at the proximal edge. This was consistent with Teo's results [10] and in contradiction to the data of Sakai et al. [9]. The good consistency in strain values meant that strain gauges could be placed in any region of the finger nail, but not close to the edges where some strain concentrations occurred.

The thumb exhibited similar behaviour to the index finger; however, there was a very distinctive pattern of localised strain fluctuation before sliding began as shown in Figure 5b. This fluctuation was made up of small areas of positive and negative strain values. The locations of greatest concentration of longitudinal strain were the distal and proximal edges. This variation possibly explains the inconsistent results achieved by Teo [10].

The lateral strain maps were broadly similar. This indicated that it should be possible to get consistent lateral strain measurements that had not been achieved in previous work.

(a)

(b)

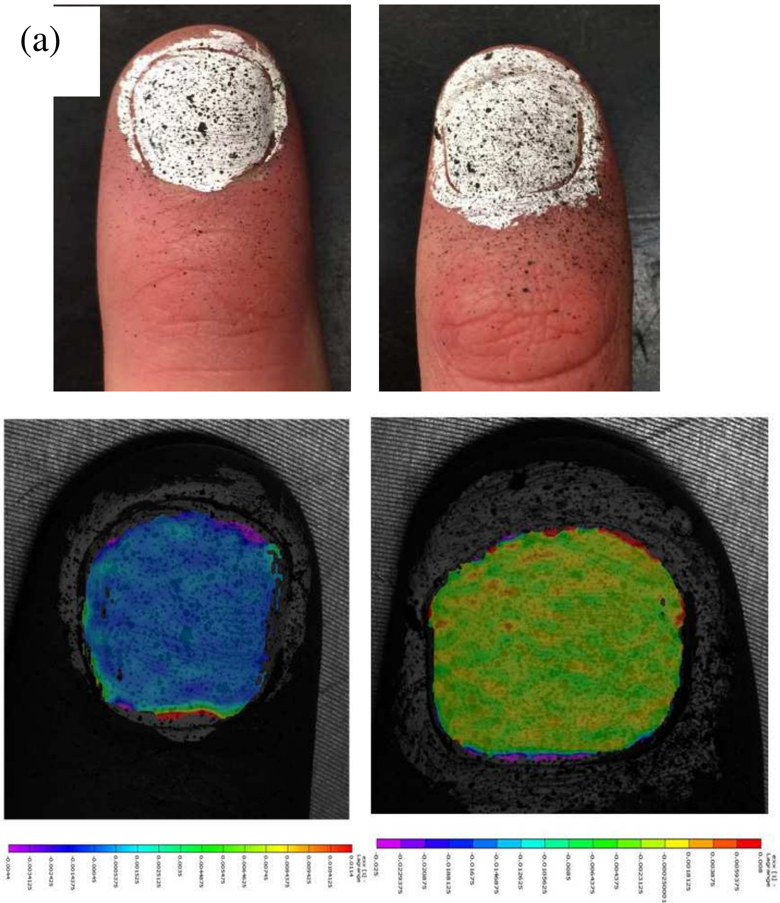


Figure 5. Digital Image Correlation on Finger Nails: (a) Speckle Pattern Applied to Index Finger (left) and Thumb (right); (b) Resulting Longitudinal Strain Maps for Index Finger (left) and Thumb (right)

The strain gauges selected for this study were TML type UFCA-1-11-3LT [15]. These strain gauges consisted of two strain sensing elements arranged at 90° recording strain along both perpendicular axes simultaneously. The strain-sensing elements of the gauge were thin foil, with a film backing. The film allowed the gauge to be bonded to surfaces and also acted as an insulator to the current carrying wire. Due to the extremely low levels of strain measured, the circuit was arranged in a quarter bridge configuration due to its very high sensitivity to strain. This configuration consists of four resistors, one of them being the active strain gauge element

For each experiment, a strain gauge was bonded to the surface of either the index finger nail or the thumb nail of the right hand of a single subject. The position of the strain gauge was distal central, as shown in Figure 6. This remained constant for all experiments. Prior to mounting the strain gauge the nails were cleaned thoroughly. The strain gauge was then transferred to a small piece of transparent tape with the exposed terminals facing upwards. A small amount of Cyanoacrylate (Loctite® Super Glue) was evenly applied to the exposed face and it was then placed on the finger nail. Pressure was applied to the strain gauge to ensure even adhesion and the glue was allowed to cure for ten minutes after which the tape was removed.

Figure 6. Index Finger with Strain Gauge Attached (before removal of tape)

2.2 Static Force Apparatus

For the static force measurements with strain gauged finger nails a multi-axis force plate (AMTI HE6X6) was used, as shown by Figure 7.

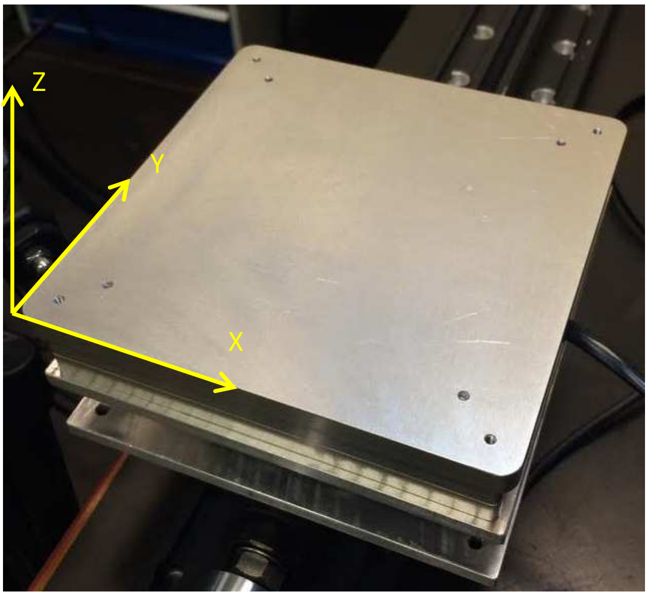


Figure 7. AMTI Force Plate and its Axes of Measurement

Once the strain gauge had been applied to the finger nail, the force plate was zeroed. The finger or thumb was positioned on the centre of the platform without applying any load (this position was recorded and re-used for all repeats). Load was then applied with the finger at an angle of 30°. The load was increased continuously from 0N to 25N, and decreased at the same rate.

Each experiment was repeated 5 times for each digit. In order to investigate the effects of rolling the finger/thumb, the procedure was repeated with the finger/thumb in varying stages of rotation. The positions investigated can be seen in Figure 8. The purpose of this was to quantify the difference in strain value for the same load applied at various stages of finger rotation about its longitudinal axis.

Figure 8. The Individual Finger Positions Investigated in Static Tests

2.3 Sliding Apparatus

For all sliding experiments it was necessary to use a linear drive to move the force plate at a constant speed, while the finger or thumb remained stationary (load was applied via a fixture above the finger/thumb, as shown in Figure 9). This was found to be more reliable than sliding the finger across the force plate. The rig was controlled via a laptop, which allowed control over both the distance moved by the force plate, and its speed. These variables were kept constant for all experiments and were 10cm and 1cm/s respectively. Loads of 5, 10 and 15N were applied.

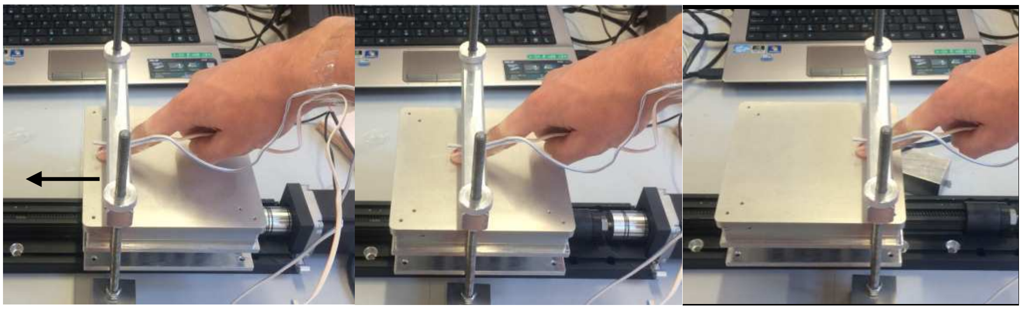


Figure 9 Sliding Friction Experiment at Varying Stages of Sliding

The experiment was repeated five times for each load. Normal force (Z-axis), tangential force (Y-axis) and finger nail strain were all recorded in relation to time.

When investigating sliding initially the force plate was zeroed. The finger was then positioned on the force plate close to the furthest edge in the Y-direction. This position was recorded and used for all repeats. The specified load was applied and maintained at a steady value. Sliding was initiated using the linear drive, causing the surface of the force plate to pass under the finger at a constant speed. The load applied to the force plate was kept constant with a finger angle of 30°. The force plate had a ground aluminium surface with a rough ness of 0.5µm (Ra).

Experiments were conducted with varying levels of lubrication in order to investigate the effects of reducing shear loading during sliding. “Dry” experiments were carried out where no lubrication was applied to the finger or force plate. In “lubricated” tests, the entire path of the finger on the force plate was lubricated. In “dry to lubricated” tests the initial path of the finger was un-lubricated until it reached an area of lubrication through which it travelled for the remainder of the slide. For “lubricated” experiments, a thin layer of Petroleum Jelly was applied to the surface of the force plate. This layer was replenished with every repeat to ensure that the same level of lubrication was maintained. For “dry to lubricated” experiments, half of the surface of the force plate was coated with Petroleum Jelly and the other left dry. For this experiment the finger was thoroughly cleaned between repeats to ensure that no lubrication was present for the first stage of the finger drag.

2.4 Data Acquisition and Analysis

Two separate data acquisition systems were required, one to record strain and one to record the force plate measurements. The strain logging system was capable of recording at a time increment of 0.00062s. This was determined by the National Instruments cDAW-9171 chassis, used to connect the strain gauges to the PC. Two channels of the same chassis (0 and 1) were used when recording longitudinal and lateral strain simultaneously. This was then connected to a PC installed with LabVIEW acquisition software. Each repeat was saved to a separate ".TDMS" file. In practice, the rate of data acquisition was, however, reduced to that of the force plate system, making comparison between the two sets more convenient whilst maintaining a high level of accuracy. The force plate was connected to a PC, which used AMTI NetForce software, to record force in each of the three axes simultaneously at a controllable time increment. This was set to one reading every 0.005s. Each repeat was saved as a separate ".txt" file.

The strain system recorded at a rate of one reading every 0.00062 seconds, which resulted in over 1500 data points each second. This rate was determined by the hardware used and therefore could not be controlled in the initial stages. In order to reduce this value it was necessary to re-process the data. The main purpose of doing this was to reduce the volume of data, making further manipulation more manageable.

The initial offset of each strain trace was recorded and subtracted from each of the final values. In order to ensure that each set of data was aligned with respect to time it was necessary to create a 'spike' in the data before the experiment began to which each set of data could be zeroed. This was done by pushing the finger onto the force plate to a value of around 20N and quickly removing it. This created a maximum value for force and strain. When processing the data, all data points before theses maximum values of force and strain were eliminated. The remaining values were then shifted with the first at time, $t = 0$. This allowed the force and strain trace for each repeat to be plotted to a single time axis.

When creating graphs to present static normal force test data, regression lines were applied due to the large number of data points, and subsequent overcrowding of the figures. For the sliding friction test data, a moving average line was applied to the strain traces at a period of every four data points. This served to remove the periodic variation of strain data which was attributed to noise, as the values of strain being recorded were extremely low.

3 RESULTS

3.1 Static Strain

Figure 10 shows the longitudinal and lateral strains for the index and finger and thumb. The different lines on each graph are repeat measurements.

The consistency of behaviour between measurements is relatively tight for both longitudinal and lateral measurements. This differs from previous work [10, 11], where there was a large spread for the lateral measurements.

The longitudinal and lateral strains are both negative, i.e., the nail is being compressed as load is applied and increased. This is consistent with work by Teo [10], but opposite to the measurements from Sakai et al. [9]. The magnitude of the strains, however, differs from Teo's work [10]. This is not surprising as the nails used in the two sets of tests would be very different in size and properties.

It can be seen that the relationship between applied force and strain is not entirely linear. For both the index finger and thumb it is until about 12N-15N and then the rate of change of strain with load decreases.

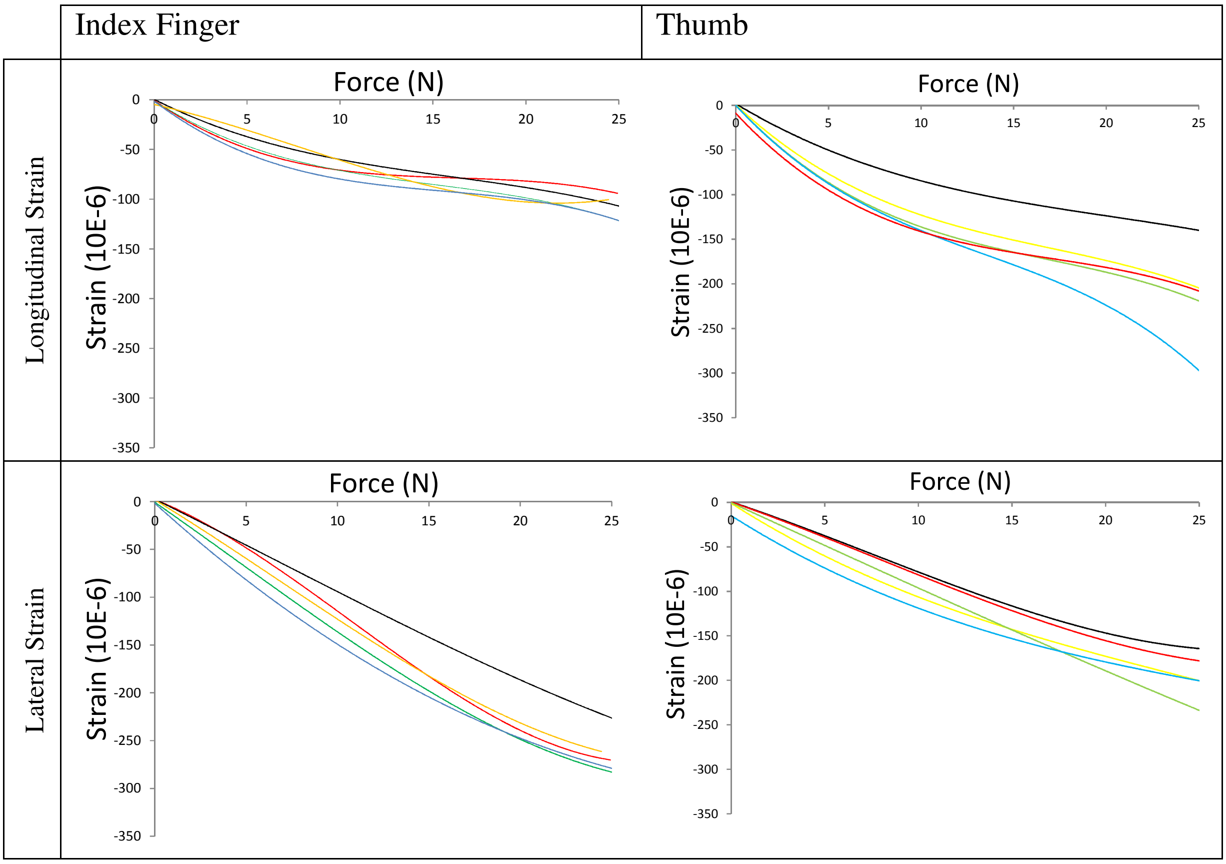


Figure 10. Lateral and Longitudinal Strains versus Load for index Finger and Thumb (each line represents a single test)

When compared to Figure 10, it can be seen in Figure 11 that the effect of rotating the index finger about its longitudinal axis to positions 1 and 3 was to reduce the strain sensitivity of the digit to normal force. Position 1 displayed a maximum strain value at around -200×10^{-6}. For position 3 this value was further reduced to around -150×10^{-6}, showing a considerable decrease in strain magnitude from the original position (position 2) at around -300×10^{-6}. A similar effect was seen for the thumb. These results indicate that any rotation in either direction about the finger's longitudinal axis will result in a reduced strain reading and therefore that finger rolling is a significant contributor to unreliable results previously obtained.

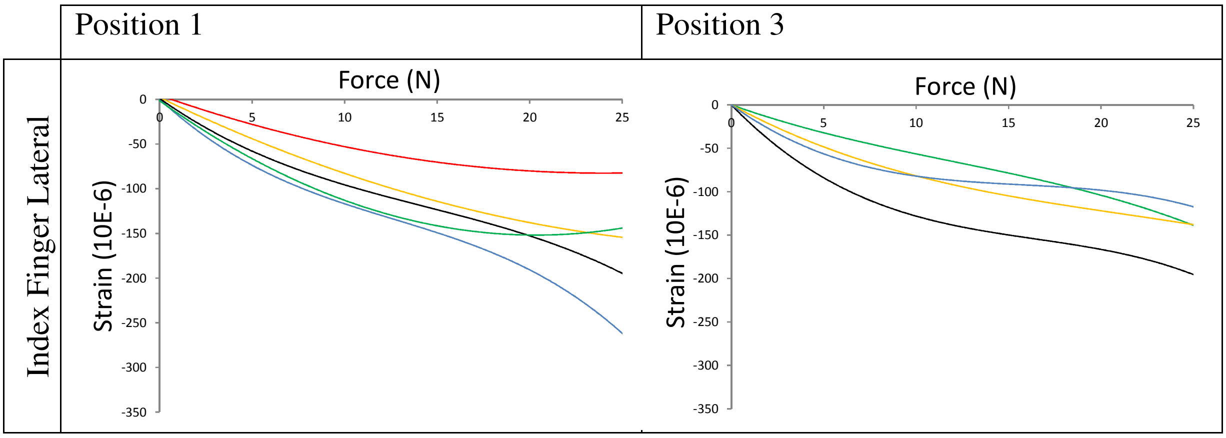


Figure 11. Lateral Strain in Index Finger and Thumb Nails at Rolled over Positions 1 and 3 (see Figure 9)

3.2 Sliding Strain

As shown in Figure 12, for dry sliding, strain increased for the index finger as normal force and shear force rose in the static region. As sliding was initiated, both longitudinal and lateral strain increased while normal force was maintained. This change in strain was greater at 10N than at 5N and 15N. Lateral strain was higher than longitudinal, as with the static measurements.

Note that there was a small level of tangential force present before the initiation of sliding for all experiments due to the difficulty for the subject in only applying load in the Z-direction.

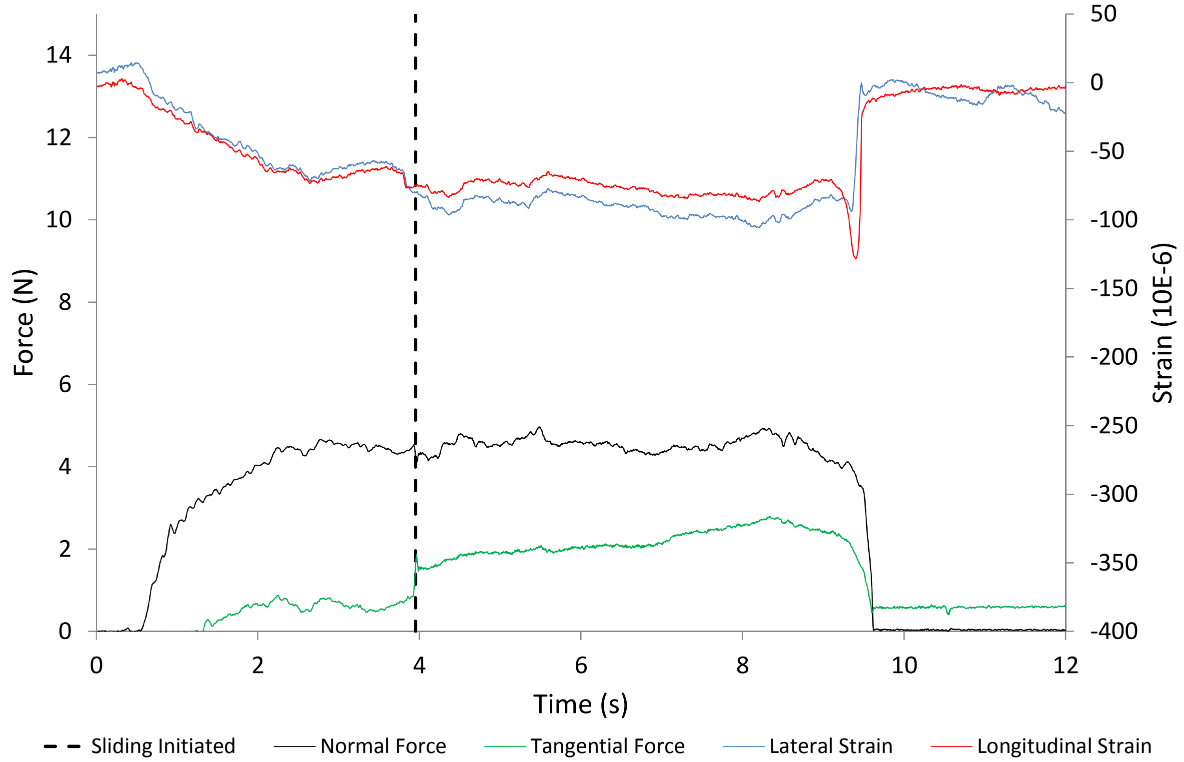
For the thumb during dry sliding at 5N of normal force, there was a noticeable increase in the magnitude of longitudinal strain at the point at which sliding was initiated, as shown in Figure 13. However, lateral strain was unaffected. As with the index finger the change in strain was highest at 10N.

It is clear from the results that while maintaining a constant normal force it is possible to use change in strain measurement to detect a change in the shear force.

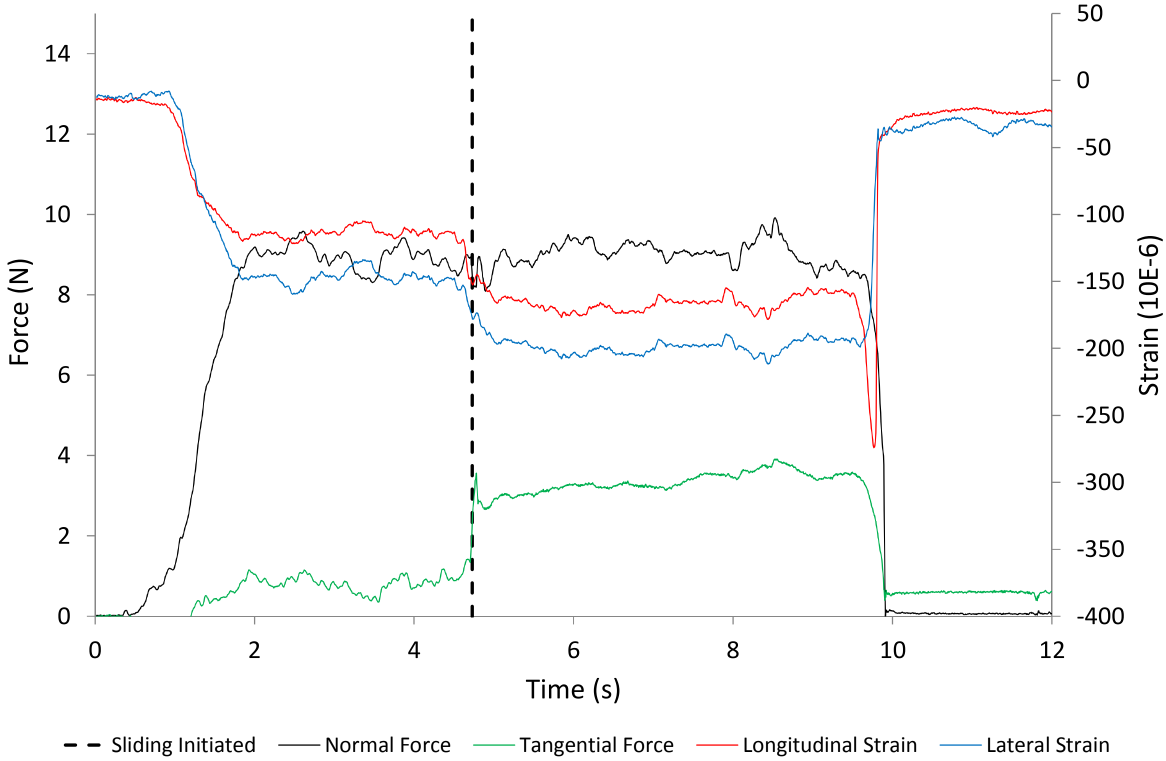
For the tests run lubricated, for which Figure 14 shows examples, there was little change in the strain measured as the index finger or thumb started sliding. The strains in the index finger were lower than those for dry sliding. As normal load was increased the strain levels increased as they did in the dry case. For the thumb the longitudinal strain levels were also lower than the dry case and increased as the normal load rose. The lateral strain, however, increased.

For the “dry to lubricated” tests there was a distinct change seen in both longitudinal and lateral strain as the finger slide into the lubricant, as shown for the index finger at 5N in Figure 15. The same was the case for the thumb.

(a)


Force (N)
Strain (10E-6)
Time (s)
Sliding Initiated
Normal Force
Tangential Force
Lateral Strain
Longitudinal Strain

(b)


Force (N)
Strain (10E-6)
Time (s)
Sliding Initiated
Normal Force
Tangential Force
Longitudinal Strain
Lateral Strain

(c)

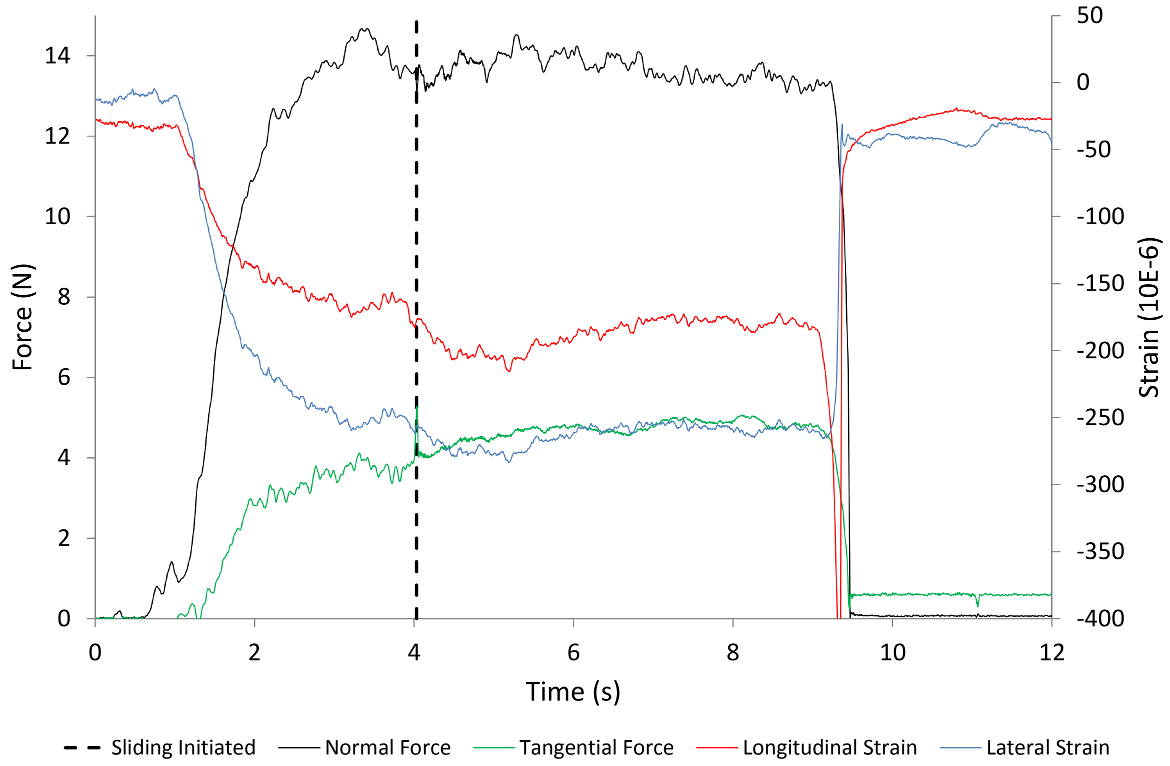


Figure 12. Index Finger in "Dry" Sliding at: (a) 5N; (b) 10N and (c) 15N

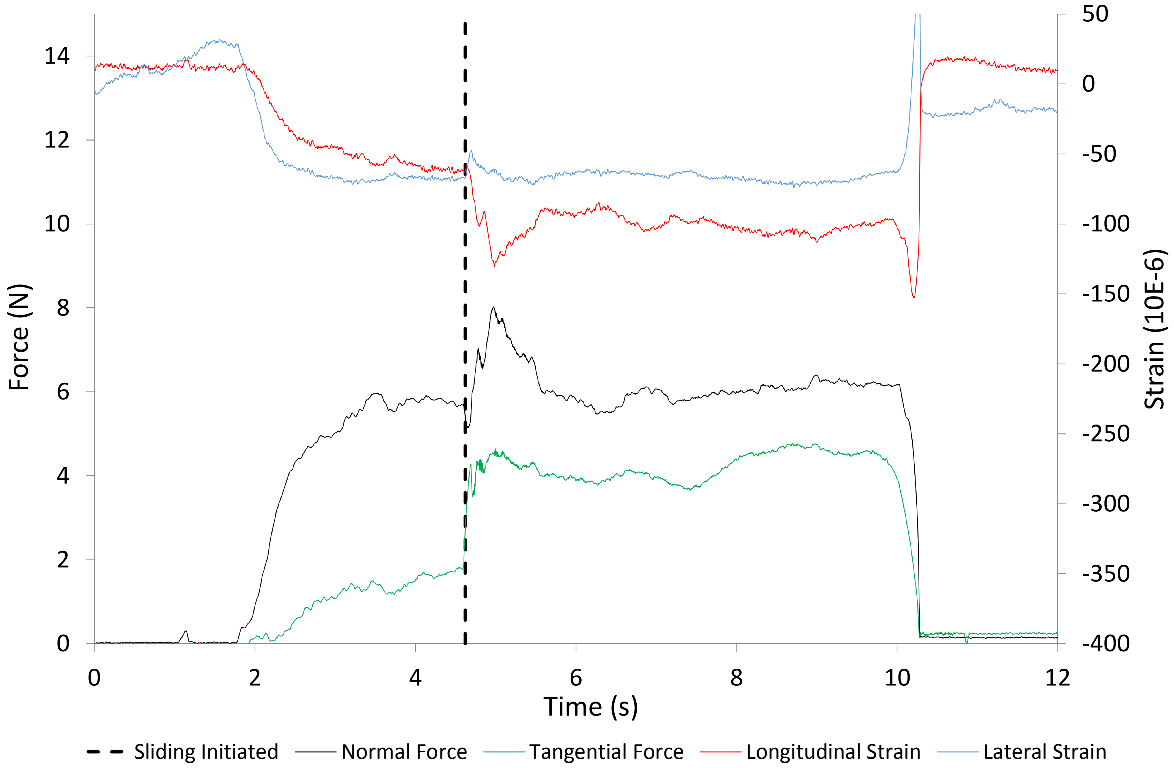
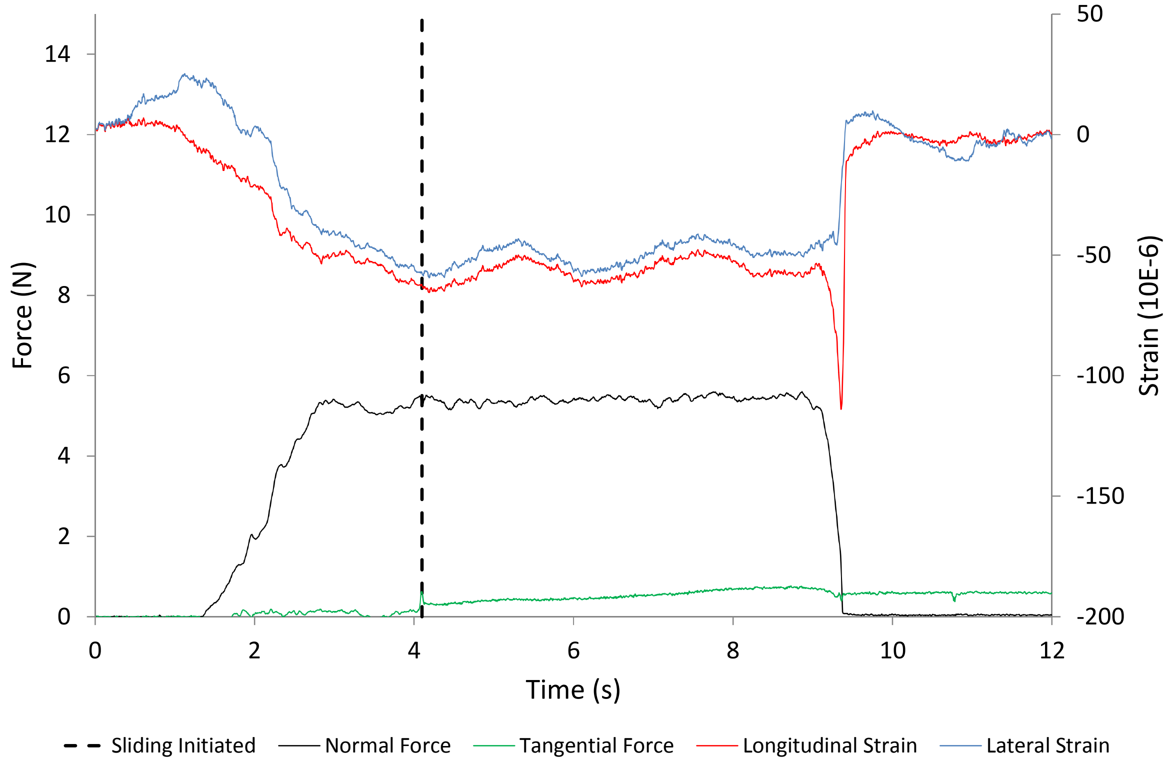


Figure 13. Thumb in "Dry" Sliding at 5N

(a)



(b)

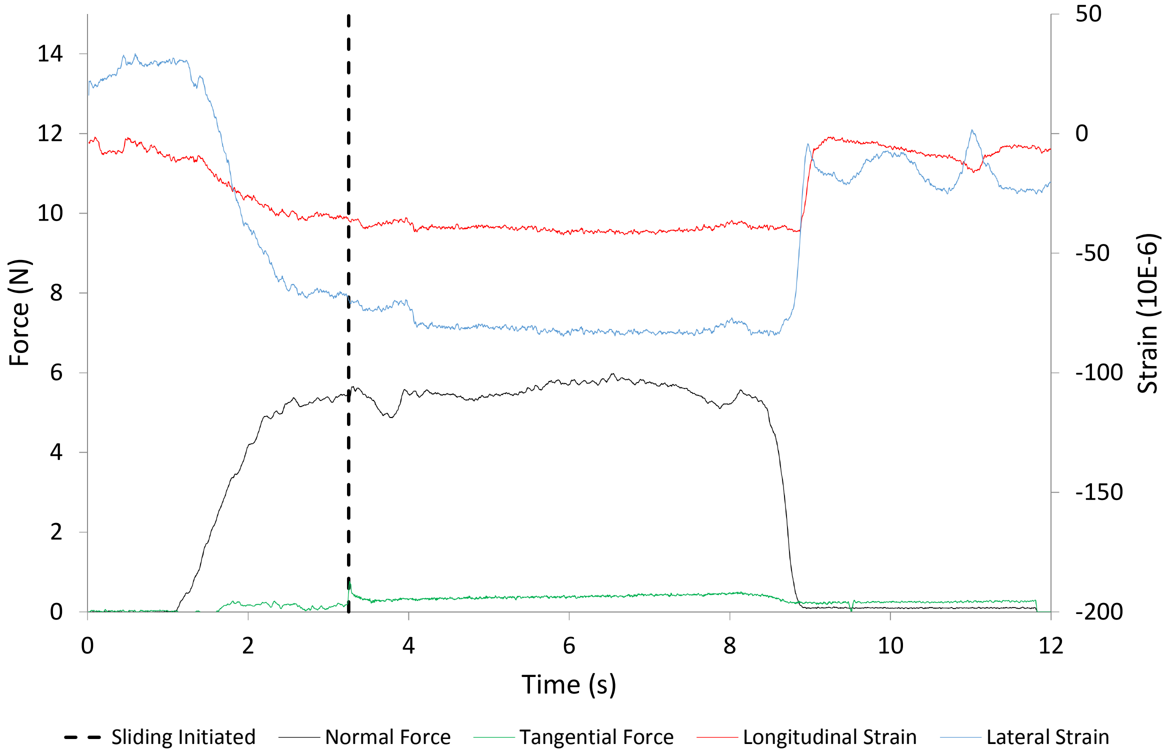


Figure 14. "Lubricated" Sliding at 5N: (a) Index Finger; (b) Thumb

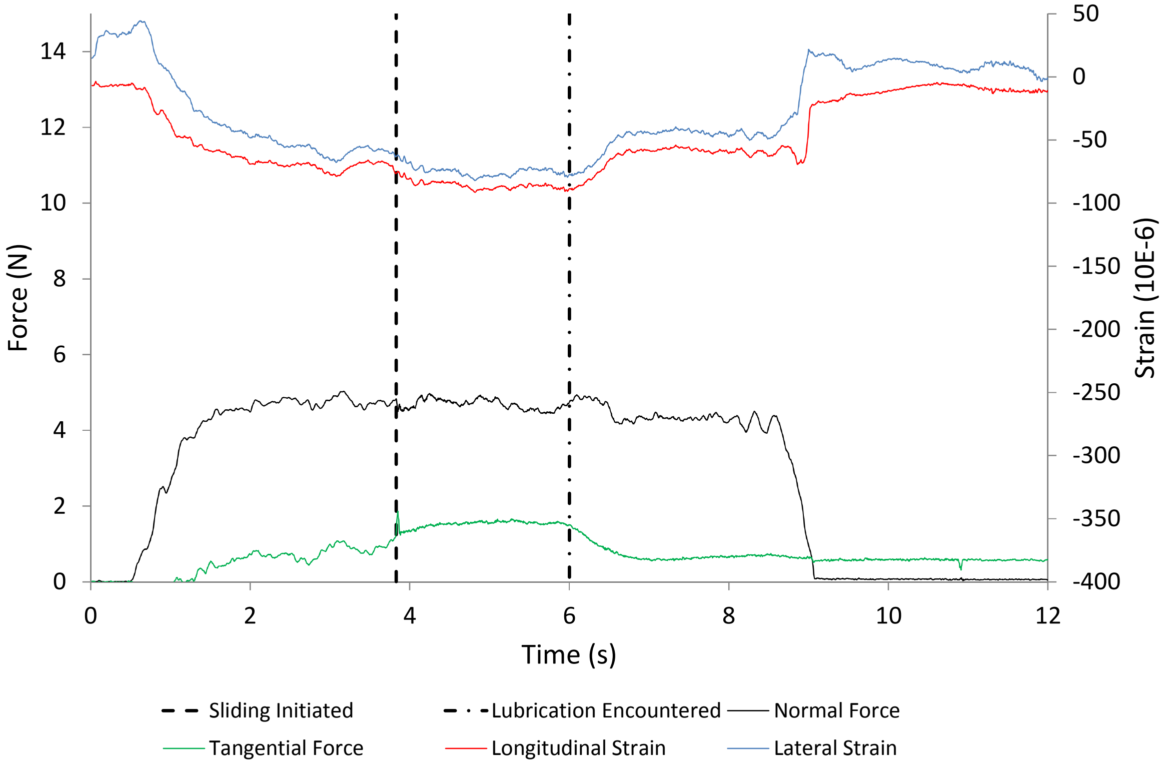


Figure 15. Index Finger in "Dry to Lubricated" Sliding at 5N

4 DISCUSSION

4.1 Normal Force

For both the index finger and the thumb, longitudinal strain began to plateau at a normal force of approximately 12N. Lateral strain, however, increased linearly with load for the entire range of force investigated. It is possible that this 'plateauing' effect was caused by the finger pad reaching its limit of compressibility and therefore ceasing to deform with added pressure. Work done by Serina et al. [16] carried out tests and analytical modelling of a finger pad. The data represents a finger being compressed onto a solid surface up to a load of 5N. The displacement of the finger pad for both experimental data and the model follow very similar paths as shown by Figure 16, with a large proportion of the displacement occurring in the very early stages of loading. After a load of around 1.5N the rate of the finger's displacement dramatically decreases with increasing load.

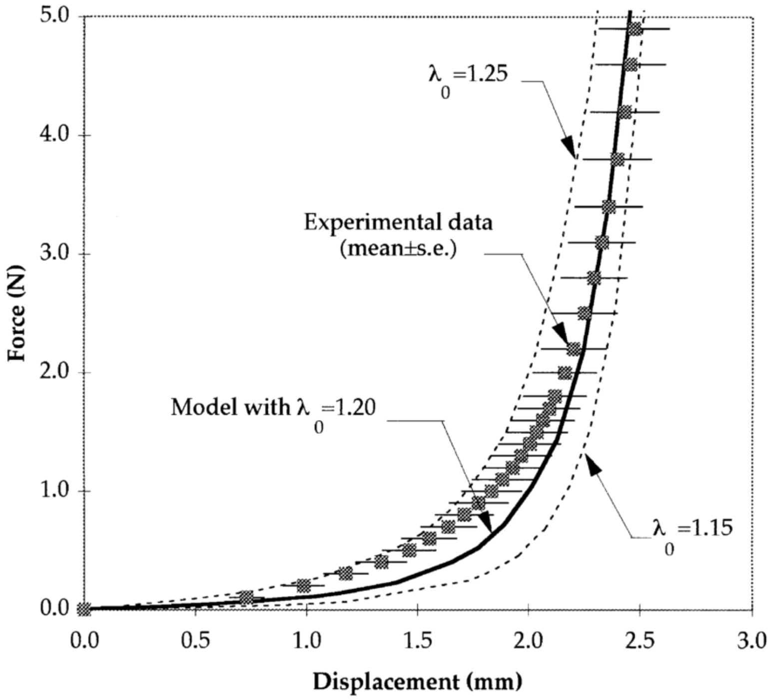


Figure 16. Displacement of the Finger Pad with Increasing Force (experimental data and analytical model) [16]

A similar trend was observed when the contact area of the finger was compared to the load applied in compression. This study supports the theory that the longitudinal strain in the finger nail or thumb nail is limited by the compressibility of the tissue beneath the finger nail, as it is less sensitive to deformation at higher loads. In the study conducted by Sun et al. [7] the change in colouration of the finger nail reached a limit at around 1N, supporting this model. For the normal force experiments conducted in this work the longitudinal strain began to plateau at around 12N as opposed to 1-2N as suggested by previous studies. This, however, may be due to the added deformability of intermediate layers between the skin and the nail plate, such as the nail bed and bone of the finger pad. This plateauing effect may explain why in the sliding tests at 15N no change in strain occurred from static to sliding, the finger pad was already compressed to its limit.

As load is applied, the pulp is displaced to the outer region of the finger pad and away from the point of contact. This reduces the volume of soft tissue between the nail and finger pad resulting in an increased modulus of elasticity of the intermediate tissue as a whole. The linear lateral strain behaviour of the finger nail may be attributed to the higher proportion of finger pulp present in the outer regions of the digit during high compressive loads, particularly in this work where a finger angle of 30° was used, allowing no pulp to be displaced towards the distal edge of the finger nail. The pulp around the radial edges of the nail is responsible for deforming it laterally at both high and low levels of loading, whereas the bone and nail bed are responsible for the deformation of the finger nail along its longitudinal axis at high loads, due to the absence of pulp at the distal edge of the finger nail.

The theory that finger pad pulp heavily influences the strain in the nail suggests that the length of the finger nail may also be an influencing factor in measured strain. The greater the length of the finger nail, the greater its area of contact with pulp at the finger's distal edge. This may be one of the reasons for a discrepancy in values of finger nail strain during the application of normal force between this study and research conducted by Teo [10]. It is likely that this effect would be a greater influencing factor on sliding experiments due to the greater volume of pulp beneath the distal edge of the finger nail.

4.2 Effects of Rolling

When the index finger was rolled into positions 1 and 3 there were significant reductions in the strain sensitivity of the nails, although a linear relationship was still evident. This can be attributed to the increased separation between the point of transmitted force to the surface and the position of measurement, which in this case was the distal central position of the finger nail. As previously discussed, the tissue between the skin's surface and the finger nail is responsible for deforming and conveying this deformation to the nail itself. If these surfaces are separated by a greater distance, there will be greater loss of deformation of the intermediate tissue and therefore a reduced reaction to load applied at the position of measurement.

4.3 Sliding

4.3.1 Movement of Pulp

One of the most significant observations made for the sliding experiments was that both strains in the index finger for dry sliding experienced a notable increase in magnitude at the point of sliding initiating. For a normal force of 15N the tangential force applied at the contact by the finger before sliding began may have been the reason for no observable strain change (see earlier comment). The thumb exhibited different behaviour in that only longitudinal strain changed upon the initiation of sliding; this difference in behaviour is attributed to the difference in geometries between each digit. When the effects were separated by conducting dry to low friction sliding experiments it was found that for both digits there was a significant decrease in the magnitude of strains experienced by both finger nails at the point at which lubrication was encountered. These results support the theory that tangential force and therefore friction influences both longitudinal and lateral strain in the finger nail of both digits.

It was discussed previously that the behaviour of finger pad pulp significantly influenced the strain in the finger nail for the normal force experiments. The movement of this pulp is also an influencing factor when measuring strain for sliding experiments as during sliding, a larger proportion of pulp shifts to the distal position of the finger pad, when compared to a non-sliding experiment, as illustrated by Figure 17. The action of sliding therefore causes a physiological change in the shape of the finger pad, which is a factor that clearly influences strain values measured as shown by the discrepancy in behaviour between the index finger and thumb. The increased volume of pulp at the distal edge of the finger pad results in a higher pressure beneath the finger nail at this position and therefore it would be expected that the finger nail would deform more significantly. This physical phenomenon would account for the increase in longitudinal strain experienced by both digits upon the initiation of sliding.

Figure 17. Schematic Showing Movement of Finger during Sliding and Relative Shift of Finger Pulp (adapted from [12])

For the index finger, it is theorised that finger pad pulp is shifted to both the distal edge and the radial edges, whereas for the thumb, pulp is predominantly shifted toward the distal edge as only longitudinal strain is impacted during dry sliding, accounting for the difference in longitudinal and lateral strain behaviour.

These results suggest that for the index finger, the tangential force experienced by a finger pad when contacting a surface influences the measured strain values. This tangential force is directly influenced by the level of friction at the interface indicating that strain gauges are effective in measuring the level of friction. It is clear, however, from all strain traces that it is difficult to distinguish between the effects of normal and tangential force, which is a significant limitation to the method. In order for the method to be effective at measuring *in-vivo* forces it is necessary be able to separate the effects of normal and frictional force on strain. For the thumb, the addition of a tangential force due to sliding only affects the longitudinal strain, so it may be easier to isolate effects of normal and tangential force.

4.3.2 Effects of Lubrication

It was observed that there was a significant drop in both longitudinal and lateral strain in the index finger for lubricated sliding compared to dry sliding. The same effect was observed for the longitudinal strain in the thumb, however, lateral strain was as high, or higher, than the dry value. This will have been mostly due to the reduced shear force. However, it is also possible that the skin properties were affected.

It was reported by Adams et al. [17] that when water was added to the finger pad surface interface, moisture diffused into the finger pad itself, lowering its modulus of elasticity and softening the skin. In this case Petroleum Jelly was the lubricant added to the contact, therefore the physiological effects of this substance on the skin of the finger pad must be considered. In a study conducted by Ghadially et al. [18] it was found that Petroleum Jelly is an occlusive substance and fully permeates into the stratum corneum, most significantly softening the outermost layer of the epidermis. Koudine et al. [19] also found that the addition of cosmetic products to the skin on the forearm had the effect of decreasing the Young's modulus and therefore softening the skin.

It is theorised that in this case the added lubricant's softening effect on the skin allowed finger pad pulp to flow more freely beneath its surface. This allowed the displacement of pulp to occur at lower loads. If this was the case then the level of friction may be independent of the strain measured and in fact, the behaviour of strains during sliding may simply be dependent on the level of moisture and lubrication present at the contact. This theory is also supported by the effects of the finger pad reaching its limit of compressibility as outlined in the previous section.

The softening of the fingertip would cause the limit to be reached at a lower value of normal force as more finger pad pulp would be displaced to the radial edges at lower loads, resulting in lower longitudinal strain values being measured when compared to experiments with no added lubrication. This effect was observed for the force application region of low friction experiments (before sliding was initiated) as the sensitivity of longitudinal strain to normal force in both digits was reduced. The separation between the longitudinal and lateral strain traces also occurred during the application of normal force and not upon sliding itself, suggesting that it is the effect of the lubrication on the properties of the fingertip rather than surface roughness that impacts finger nail strain.

5 CONCLUSIONS

This work was successful in its aim of establishing confidence in the existing method of measuring finger pad force using strain gauges mounted on a finger nail. It was found that rotation of the finger about its longitudinal axis had a significant effect on reducing the sensitivity of strain in both measured orientations for both digits, and it is likely that this was the main cause of discrepancies in previous studies. It was found that under low normal loads, displacement of finger pad pulp is the dominant factor influencing the measured strain. Above loads of approximately 12N the longitudinal strain in both digits plateaued as the compressibility limit of the fingertip pulp had been reached. Above this threshold the magnitude of lateral strain continued to increase linearly as lateral deformation is dominated by the mechanism of pulp shift.

It was found that friction had a transient effect on both longitudinal and lateral strain measured in the index finger nail and in the longitudinal orientation for the thumb. These effects were attributed to the difference in geometries between digits and subsequent difference in pulp behaviour under shear. The overall magnitudes of both strains during sliding were found to be reduced for the index finger in both orientations and the thumb in the longitudinal orientation for lubricated compared to dry sliding. This was attributed to the lower shear force and effects of lubricant softening the epidermis. The shift of finger pad pulp upon shear force being applied at the contact is also a likely cause of the increase in strain magnitude with dry sliding. It is not clear as to which of the two mechanisms is dominant in influencing the measured strains. There was a notable difference in strain between the high and low friction situations investigated for both digits, however, in the situation of handling an object there is no way of separating the effects of normal and frictional force on strain.

Strain gauges mounted on the finger nails could be an effective method of measuring normal forces experienced by the finger nails, however, in order for this method to be effective at measuring friction, it must be possible to separate the effects of different types of loading.

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